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Title: New accelerator capabilities with the high-gradient C-band

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New accelerator capabilities with the high-gradient C-band

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AOT-AE

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Outline of this talk

- Introduction: mission need, why Los Alamos, and why C-band

- C-band activities
  - ✓ High gradient C-band test stand and cavity testing
  - ✓ Cryo-cooled cavity capability development
  - ✓ High gradient pRad upgrade
  - ✓ Breakdown theory – new research direction for materials in extremes

- Summary and near term plans

Introduction

Immediate needs for accelerator capability development at LANL

LANSCE accelerator upgrades:

Applications such as pRad desire higher proton beam energy
→ add a booster to current LANSCE linac to increase beam energy to 3 GeV

New capabilities: improve accessibility

Material science at LANL will benefit from powerful directional high repetition rate X-ray sources
43 keV photons can be produced with 42 MeV electron beam
43 keV photons are DMMSC relevant

Compact Accelerators: enabling feasibility

As it considers itself to be the NNSA accelerator laboratory, LANL should play role in developing compact accelerators for various national security missions.

Accelerator capability: example 1

43 keV Inverse Compton Scattering (ICS) source

Accelerator frequency	5.712 GHz
Accelerating gradient	84 MV/m
Length of the accelerating structure	0.5 m
Electron bunch charge	100 pC
Laser's wavelength	800 nm
Laser's pulse length	40 fs
Laser's pulse energy	100 mJ
Electron beam energy	42 MeV
X-ray photon energy	43 keV
Number of X-ray photons per pulse	$2.2*10^7$

Accelerator capability: example 2

pRad upgrade to 3 GeV proposed accelerator structure parameters:

Frequency, GHz	Velocity β	Total length, m	Accelerating gradient, E_oT (MV/m)	Shunt Impedance, MΩ/m	RF Power, MW
1.40875	0.84	1.6	12	68.6	8
2.8175	0.84 – 0.93	31.8	36	69.9 - 83.4	432
5.635	0.93 – 0.97	20	100	76.9 - 96.9	1500
1.40875	0.97	9	12	77.0	50

Reasons to increase gradient

LANSCE accelerator upgrades: cost scales as size (length) of the accelerator.

$L \sim V_{beam}$ / Gradient

→ double the gradient, halve the cost

New capabilities: improve accessibility

Higher gradients → same beam voltage in smaller space

Same voltage → similar output (e.g. X-ray energy)

Smaller space → enters range of accessibility for various needs

More installations → more science enabled

Compact Accelerators: enabling feasibility

Higher gradients → higher voltage in a given size

Higher gradients → target voltage with a smaller system

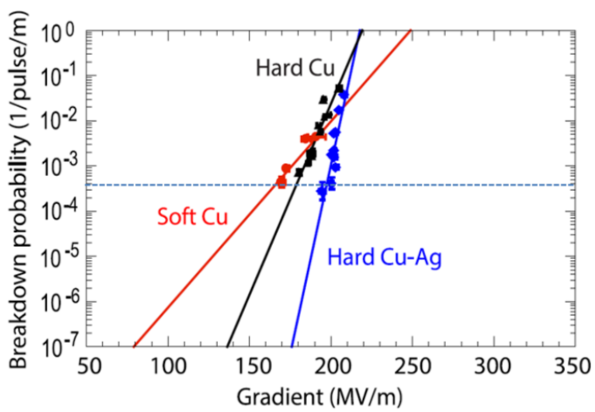
Impacts viability of concepts for surveillance, accelerators-in-space, etc.

Gradient limits

The gradient of copper-based accelerators is limited by *breakdown*.

Breakdown is what it sounds like: the surface of the cavity breaks down, and, in essence, an arc discharge forms within the cavity.

Breakdown can happen at any gradient; the figure of merit is the *probability* that it will happen at a given gradient.



Why Los Alamos

Achieving high-gradient performance (low breakdown rates, low field emission, new materials for HOM absorption, etc.) is a *materials science* problem.

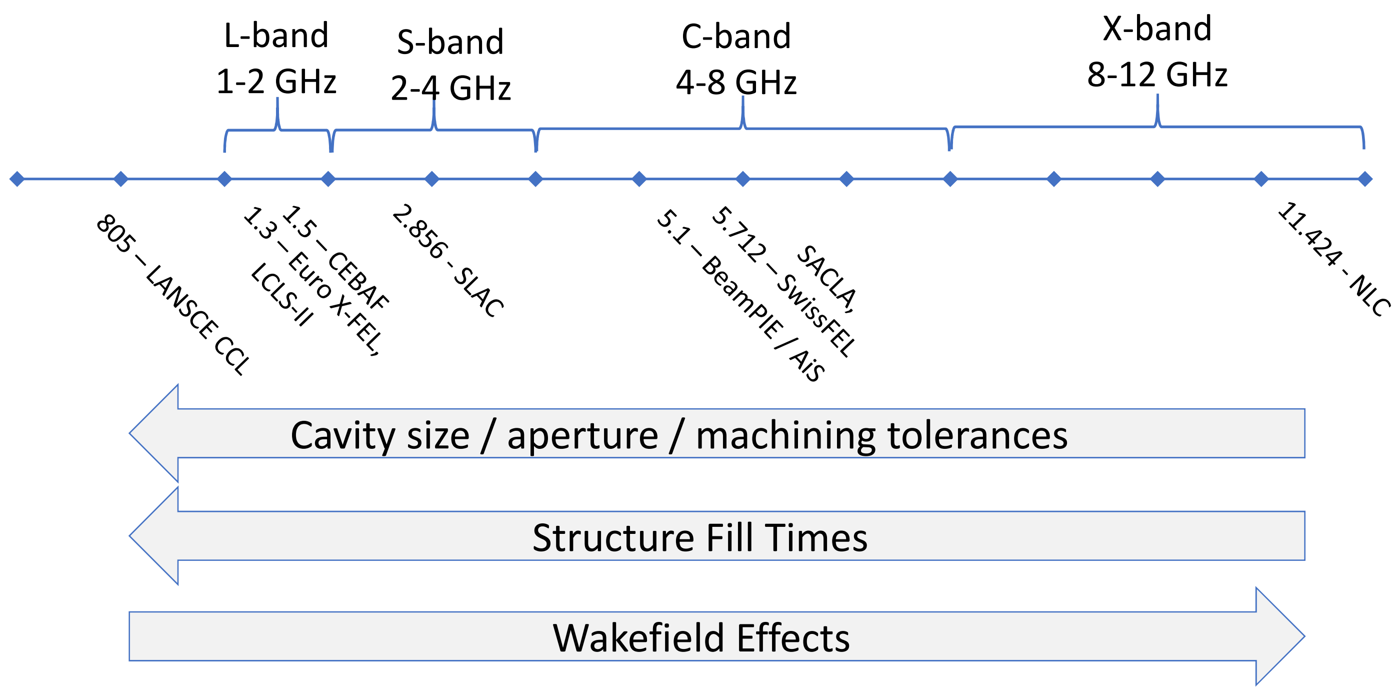
Los Alamos is, at core, a materials science laboratory.

Los Alamos also considers itself the steward of accelerator science for the NNSA part of the DOE complex.

Thus, Los Alamos has both an institutional interest in, and capability to address, this problem space.

High gradient C-band work directly aligns with future NNSA and LANL missions.

Why C-band ?



C-band is *convenient*, for a number of metrics, for high-performance accelerators. In particular, a naturally "good fit" to hard X-ray FELs.

Technical goal of the C-band program at LANL

- Develop structures that operate reliably at high gradient (up to 100 MV/m).
- Develop structures capable of efficient operation in a long pulse regime.
- Develop structures delivering high quality beams.

C-band Engineering Research Facility (CERF-NM)

Overview of LANL High Gradient C-band DR project

The goals for LANL's high gradient DR project are

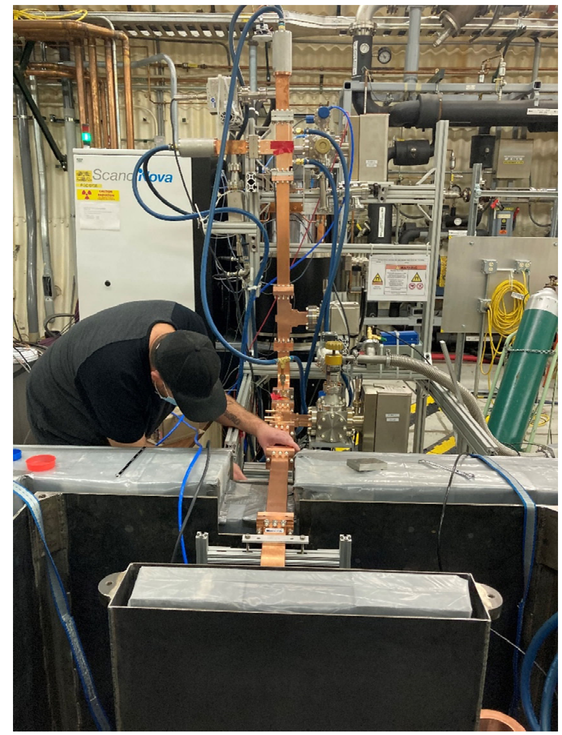
- To establish the benchmark point for the rf breakdown probability at C-band (5.712 GHz).
- To conduct material studies.

LDRD 20200057DR

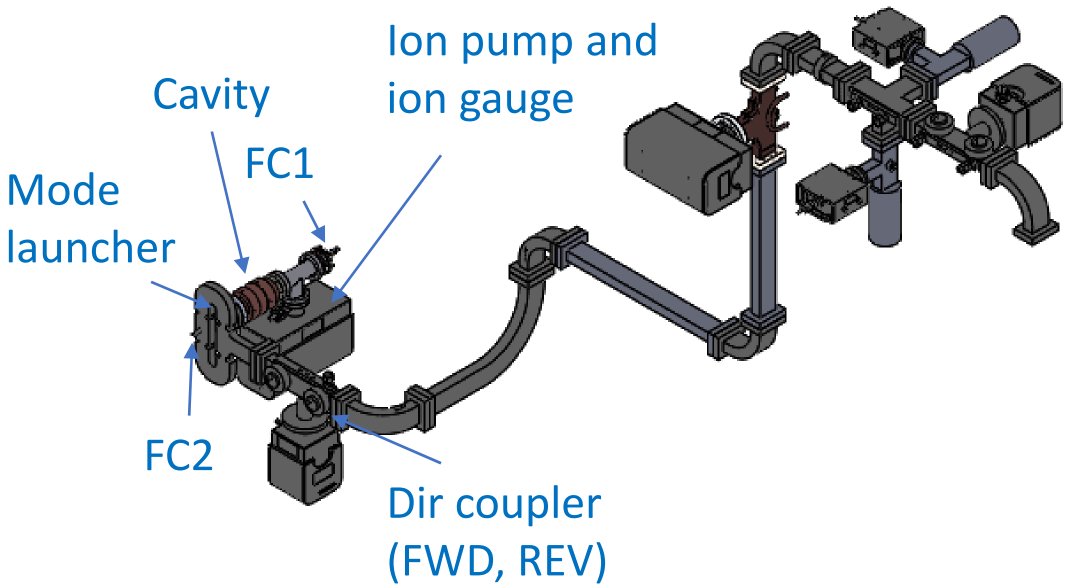
LANL C-band Engineering Test Facility (CERF-NM)

UC XFEL collaboration will leverage about $3M of LANL's internal infrastructure investment.

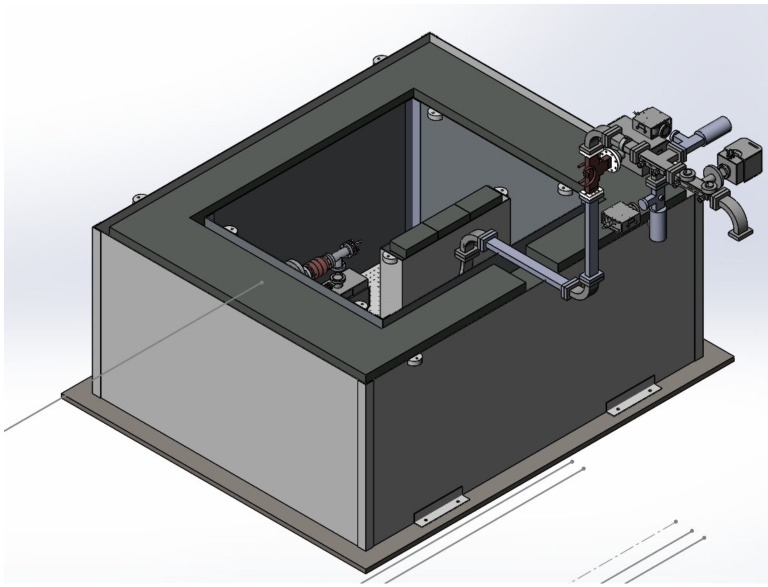
- Powered with a C-band Canon klystron
- Conditioned to 50 MW
- Frequency 5.712 GHz
- 300 ns – 1 µs pulse length
- Rep rate up to 200 Hz (typical 100 Hz)
- Nominal bandwidth 5.707-5.717 GHz



Schematic of the C-band test stand

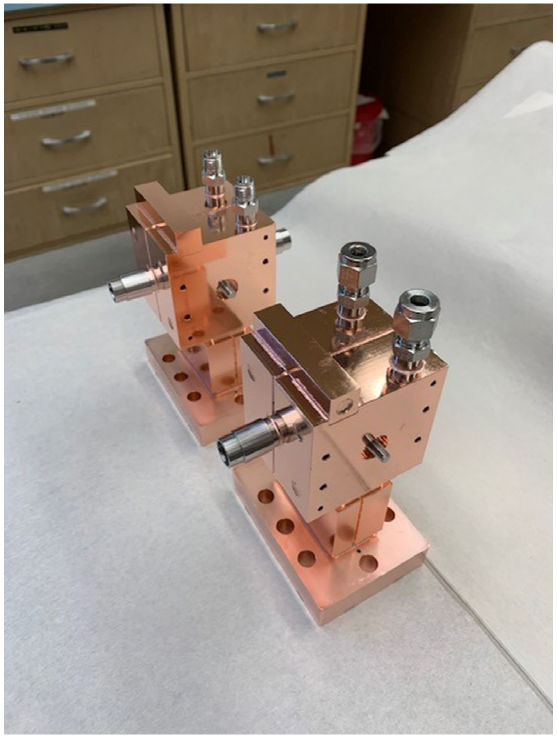


Radiologically certified for dark currents up to 5 MeV and 10 µA.



First high gradient cavities tested at CERF-NM

- LANL's high gradient C-band test facility is the only high gradient C-band test facility in the US and is open to collaborators.
- LANL provided us with Technology Evaluation and Development (TED) funding to test SLAC's C-band beta=0.5 cavities at high gradient.
- SLAC delivered two cavities to LANL: one made of copper and another one made of copper-silver alloy.



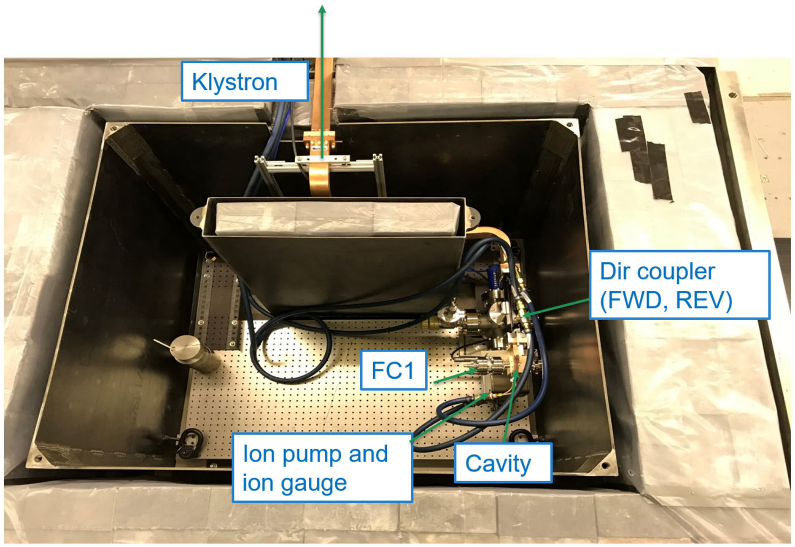
Los Alamos NATIONAL LABORATORY

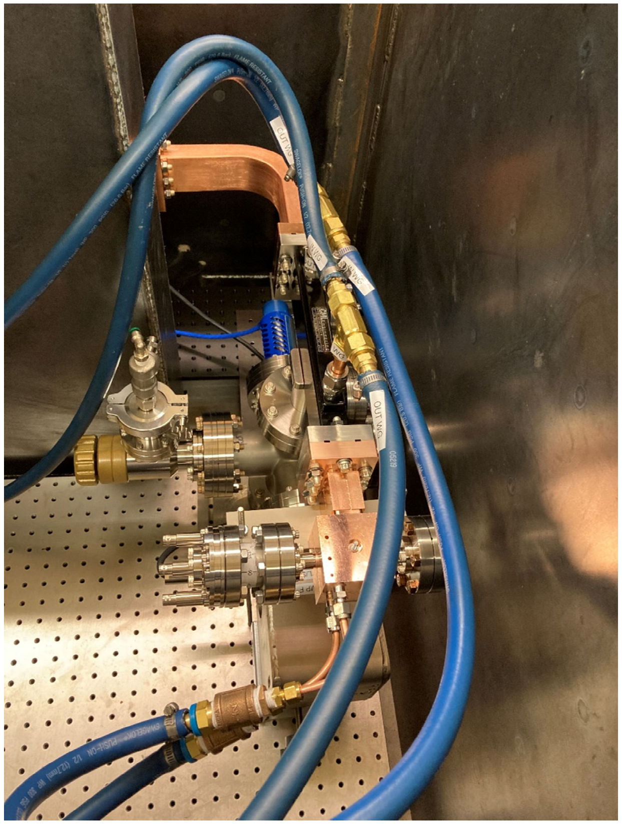
U.S. DEPARTMENT OF ENERGY Office of Science

RF cavity testing at C-band

This C-band high gradient test facility is internationally unique. The first cavity tested at the facility was produced by SLAC.

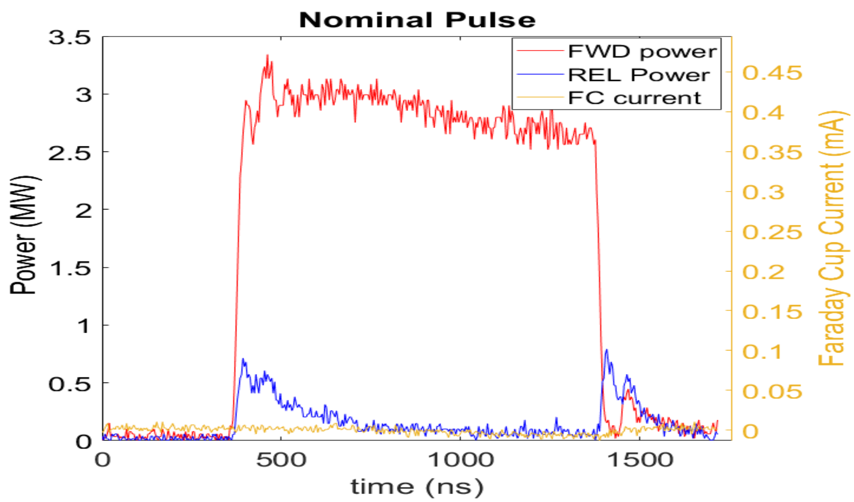
- The RF cavities are installed at the end of the waveguide line inside of the lead box.
- Lead box is rated for dark currents up to 5 MeV.
- Diagnostics includes a directional coupler for forward and reflected power, Faraday cups, and temperature sensors.

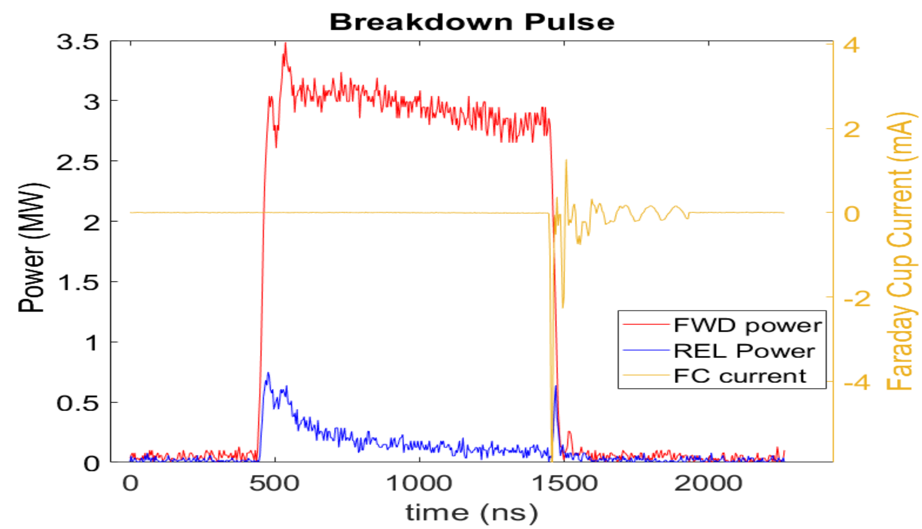




Current test status

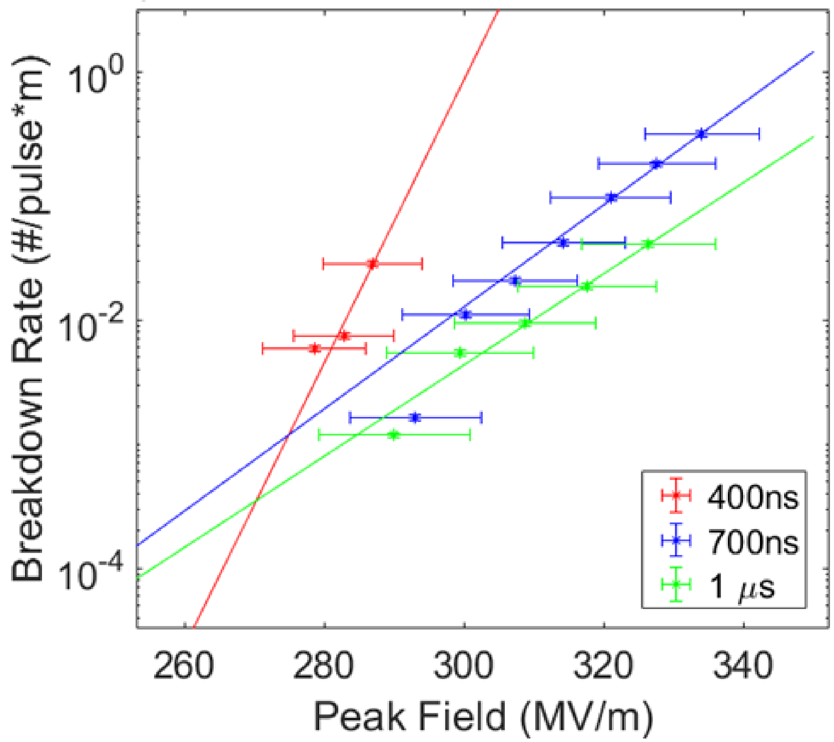
- **Two cavities are conditioned to the maximum gradient at pulse lengths of 300 ns, 400 ns, 700 ns, and 1 microseconds.**
- Peak surface electric fields in excess of 300 MV/m demonstrated
- Breakdown probabilities are measured.





Breakdown statistics for the copper cavity

- Breakdown probability was recorded for three different pulse lengths.
- First high gradient testing of a C-band accelerating cavity in the US.
- Achieved peak surface electric fields are about 20 per cent lower than at X-band (11.424 GHz).

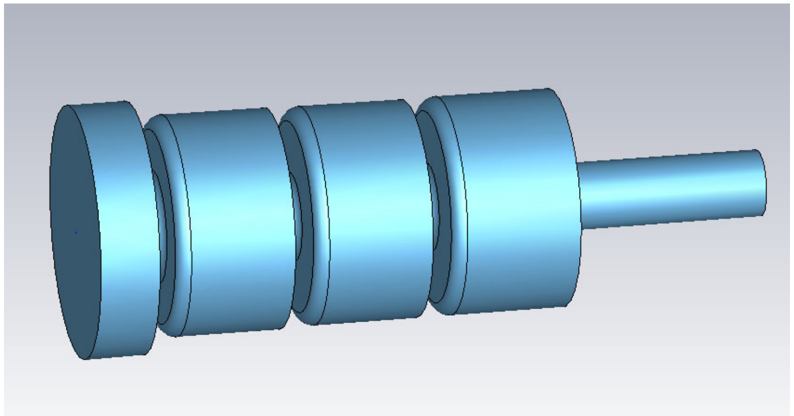


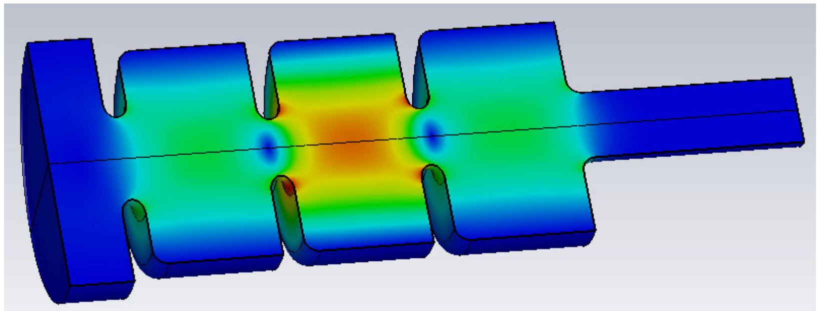
C-band a/λ=0.105 benchmark cavity

Several cavities currently in fabrication:

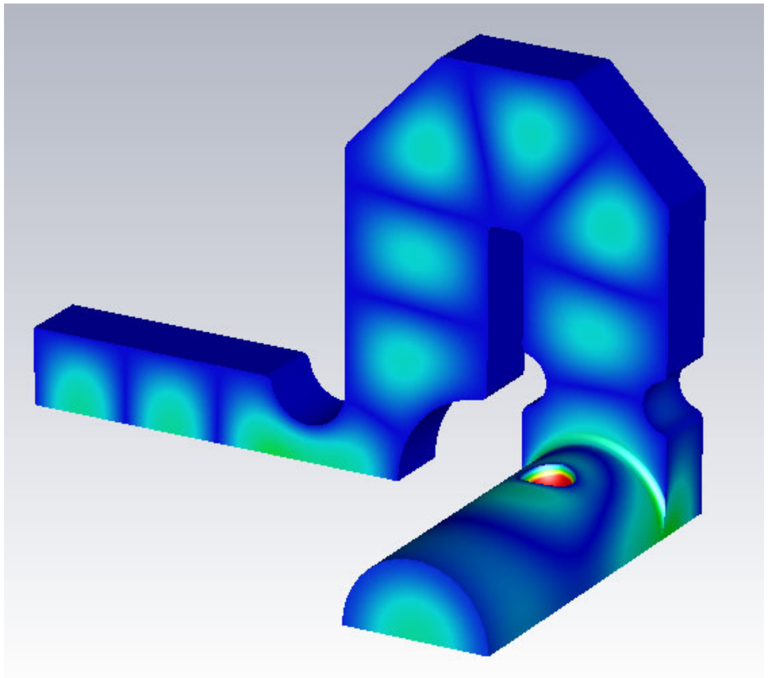
- Copper + brazed
- Copper + welded
- Copper-silver, 0.085% silver
- Copper-silver, 2% silver

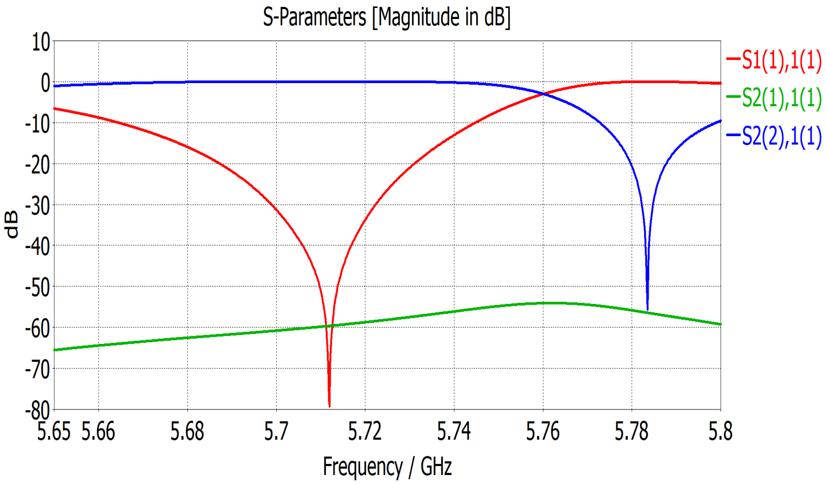
Frequency	5.712 GHz
Phase shift per cell	π
Cell length	1.034 in
a/λ	0.105
Iris radius	0.217 in
Q(copper, RT)	12700
Power for 200 MV/m surface field	5.3 MW





LANL mode launcher

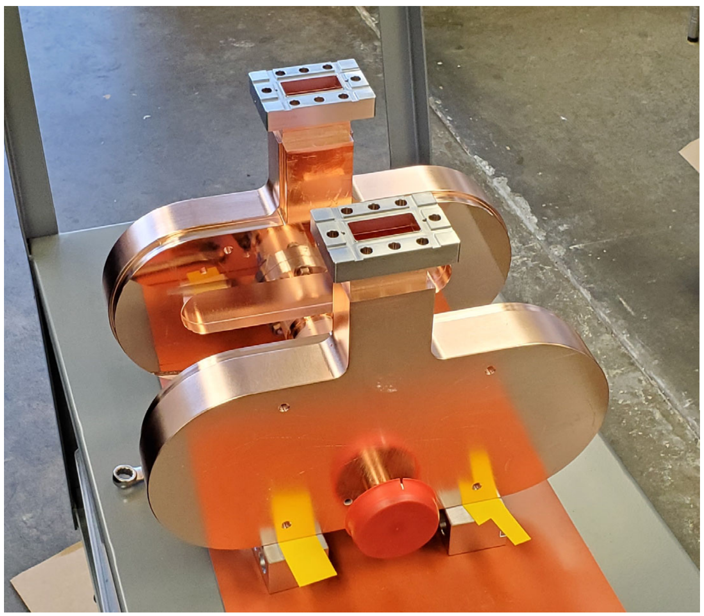


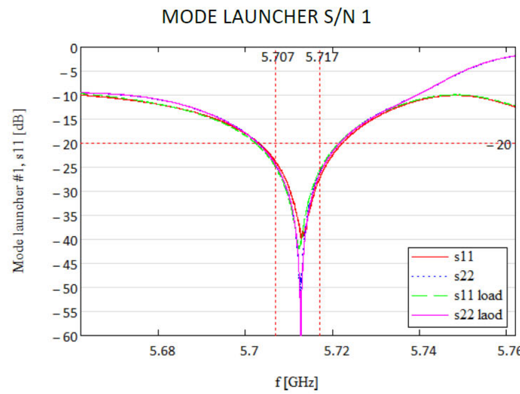


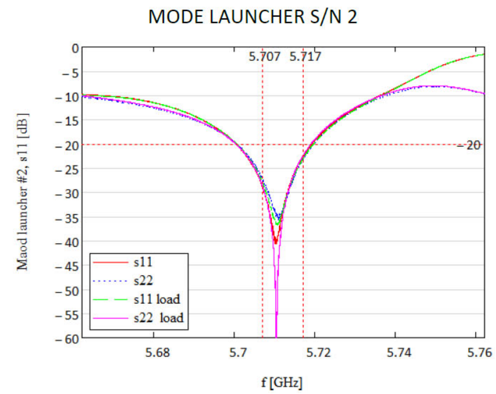
Bandwidth @-20 dB	17 MHz (5.703 to 5.720 GHz)
Emax for 25 MW power	15.34 MV/m
Hmax for 25 MW power	46.9 kA/m
Pulse heating for 1 μs pulse	0.67 °C

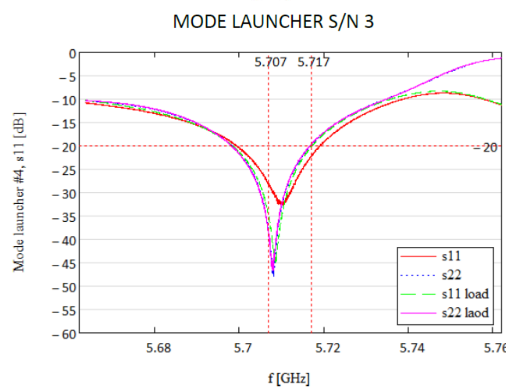
Mode launcher fabrication and cold-tests

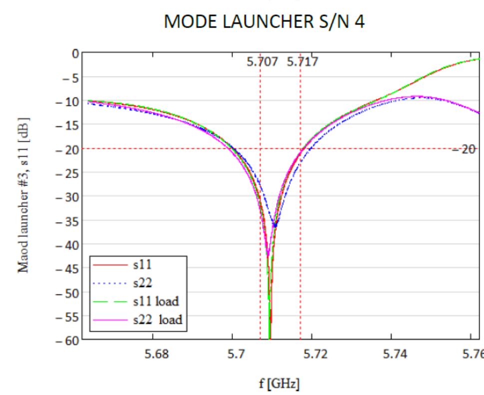
Fabrication of 4 mode launchers was performed at Dymenso, LLC. in collaboration with Philipp Borchard.











C^5: Cryo-cooled copper cavity capability

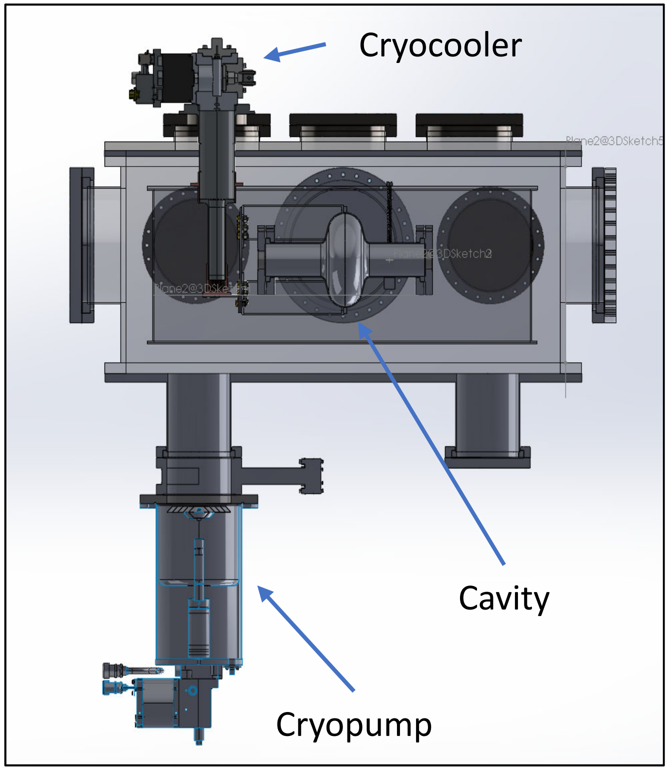
Cryo-cooled copper cavity testing capability

- Operating at cryogenic temperatures (80 K and below) reduces breakdown probabilities and RF power requirements.
- Four times lower RF losses in copper at temperatures of 40K and below compared to room temperature.
- Cooling power needed for 300 ns pulse length, 100 Hz rep rate, 200 MV/m peak surface field - 40 W, 300 MV/m peak surface field – 90 W.

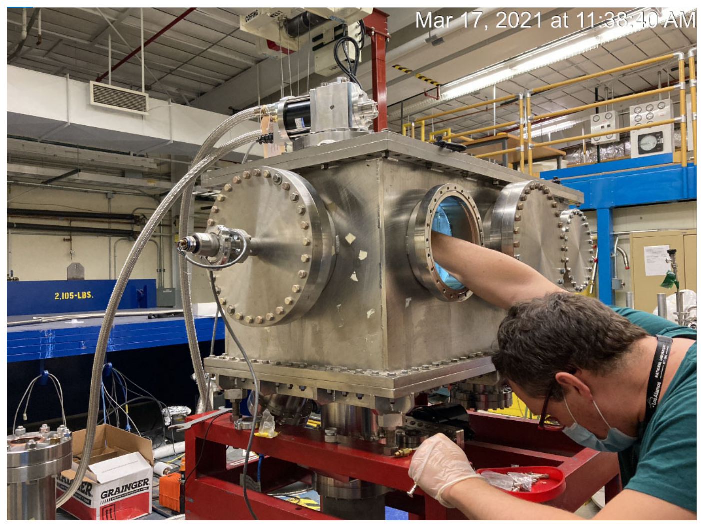
Sumitomo 4K cryo-cooler

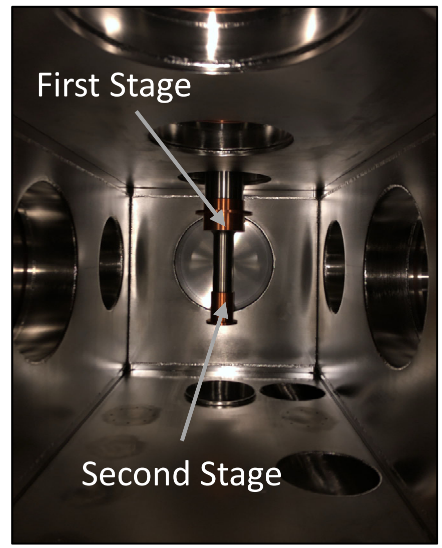
Cold Head Model		RDK-415D
1st Stage Capacity	50 Hz	35 W @ 50 K
	60 Hz	45 W @ 50 K
2nd Stage Capacity	50 Hz	1.5 W @ 4.2 K
	60 Hz	1.5 W @ 4.2 K
Minimum Temperature[2]		<3.5 K
Cooldown Time[2]	50 Hz	<60
	60 Hz	<60
Weight		18.5 kg (40.8 lbs.)

Cryo-cooling chamber

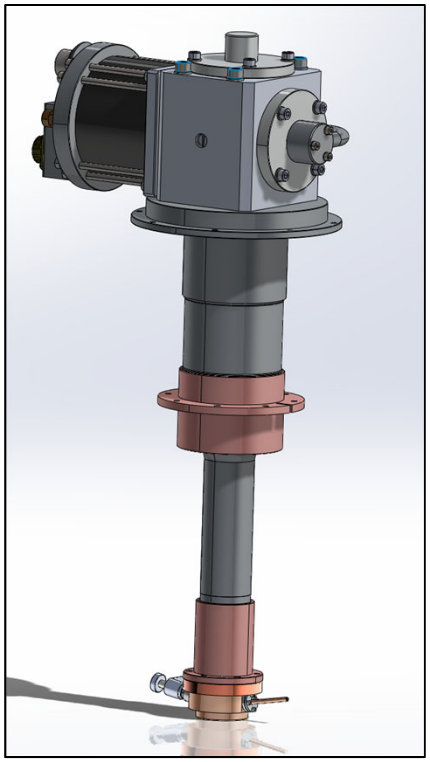


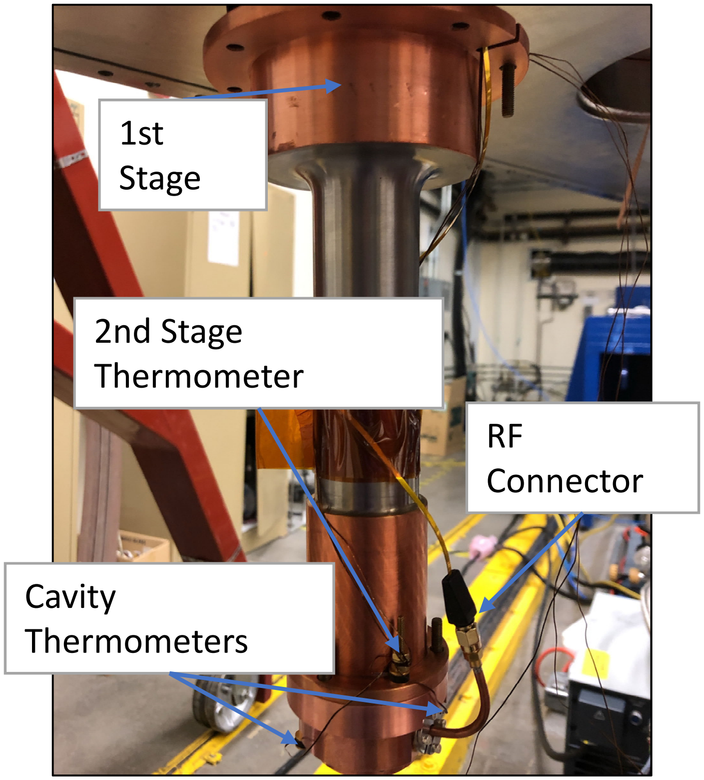
- Vacuum system
  - Scroll pump – 600 L/min
  - 8” Cryo pump – 1,500 L/s (air), 4,000 L/s (water)
  - Lowest pressures achieved:
    - 1E-7 Torr with no cryocooler, 1E-8 Torr with cryocooler

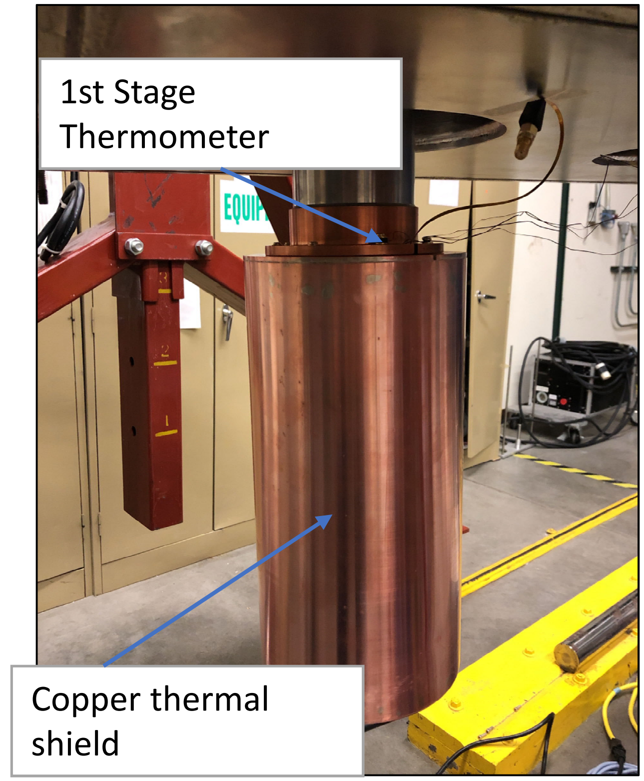




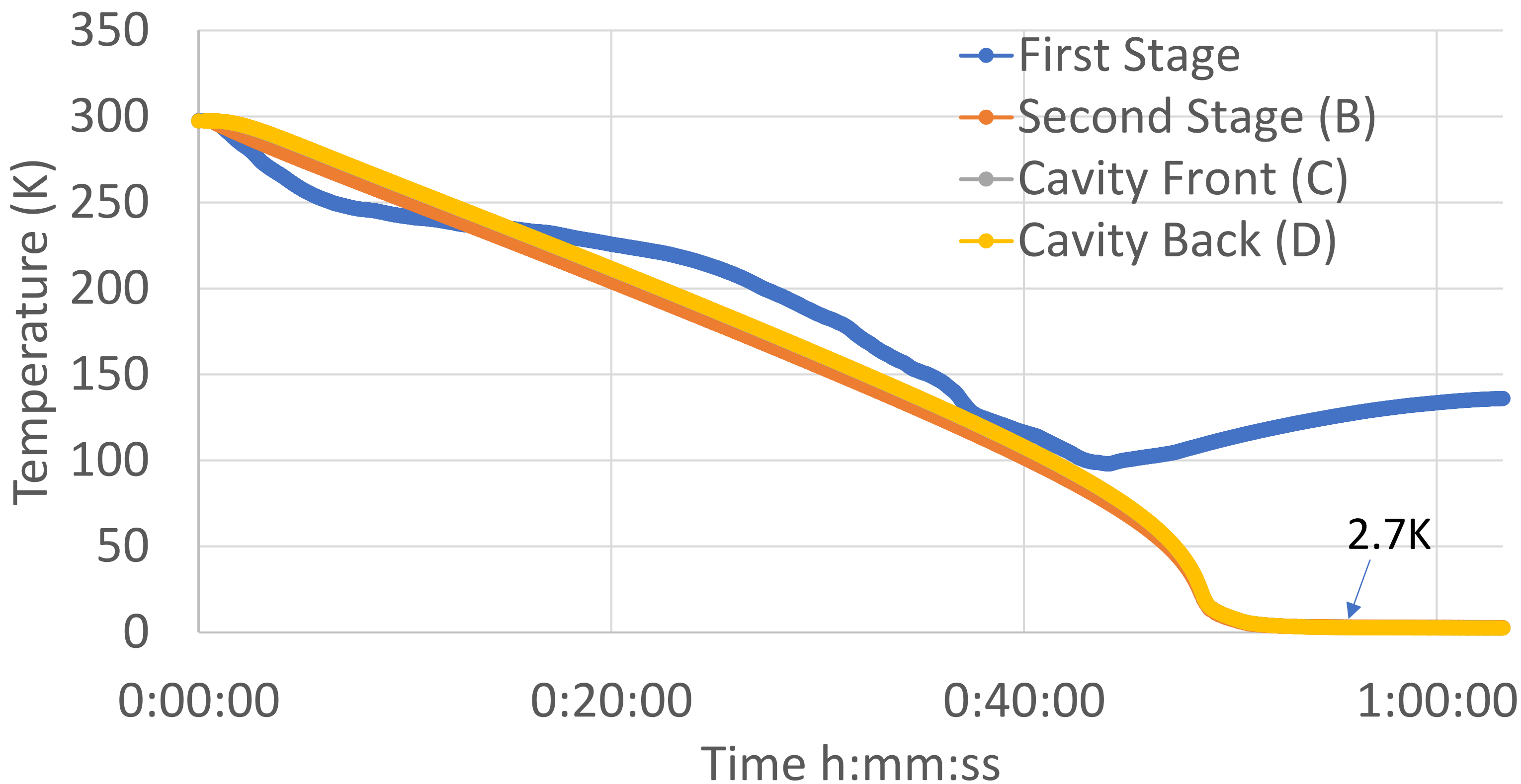
5.1 GHz cavity cryo-cooling test





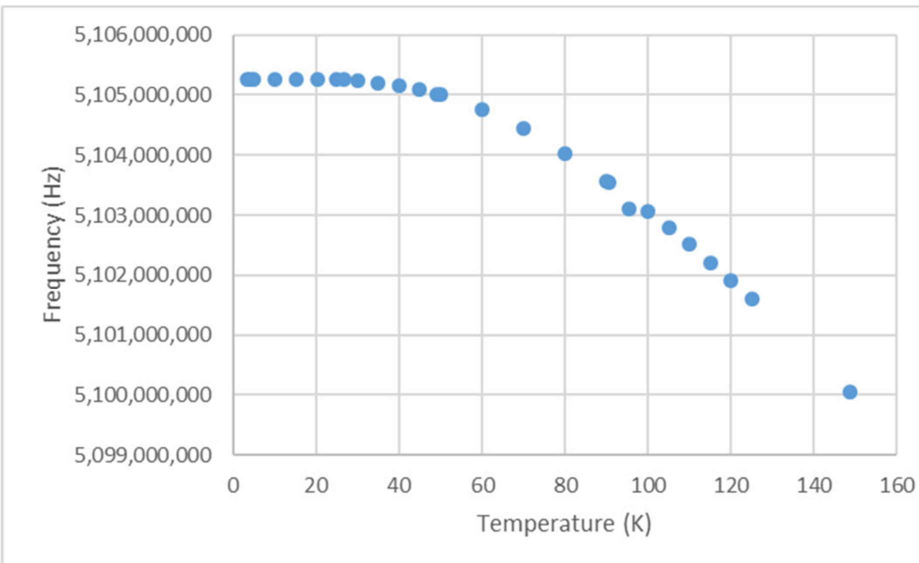


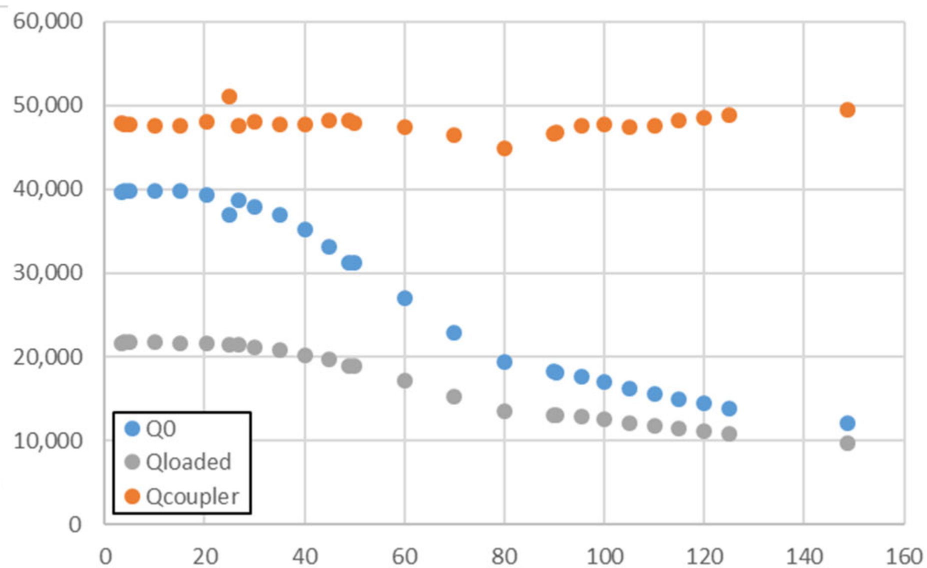
5.1 GHz cavity cooldown



5.1 GHz cavity's behaviors versus temperature

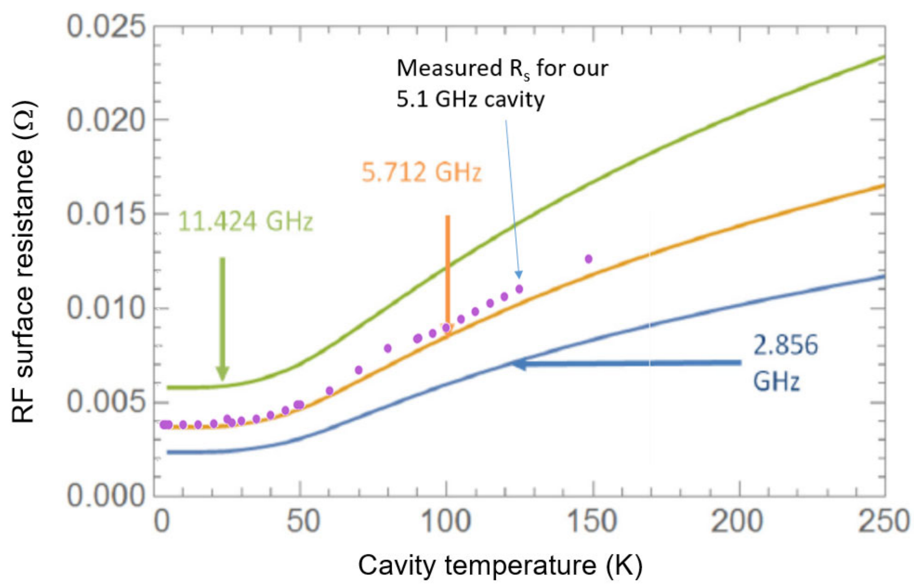
Q_o depends on surface resistance and goes down with temperature as expected.
Coupler Q is determined by geometry and does not vary much with temperature.





Surface resistivity: calculations vs. measurements

Theoretical curves assume RRR=400 copper (very high conductivity). The 5.1 GHz cavity (made by SLAC) is most likely OFE copper, which typically has RRR = 100-200 (higher resistance than used for the theoretical calculations).



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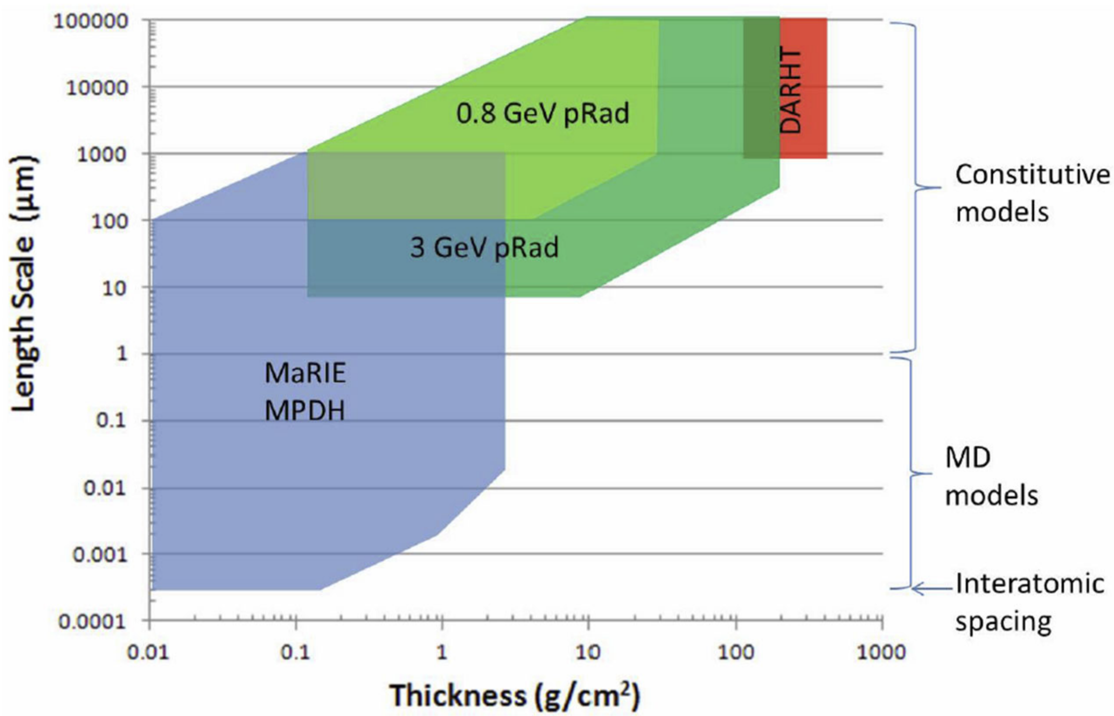
3 GeV pRad booster concept

Radiographic Capabilities of the 3-GeV Proton Radiography

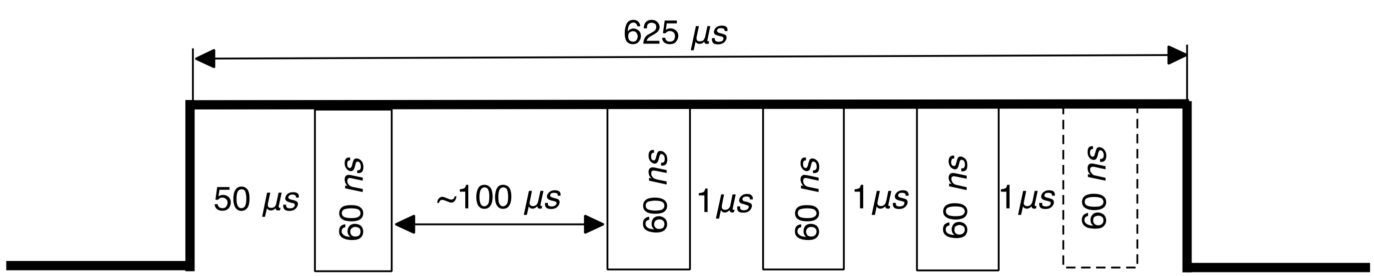
- Increasing the proton energy from 800 MeV to 3 GeV improves the radiography resolution by a factor of 10.
- Bridges the gap between DARHT and future DMMSC, which can provide the finest resolution.
- Allows for thicker objects and finer resolution than current pRad.



Parameters for Existing and Upgraded pRad

	Existing	Upgraded
Energy (GeV)	0.8	3
FWHM momentum spread, dp/p	1×10^{-3}	3.3×10^{-4}
Beam current / bunch (mA)	10	19
Protons per pulse	5×10^{9}	9.5×10^{9}

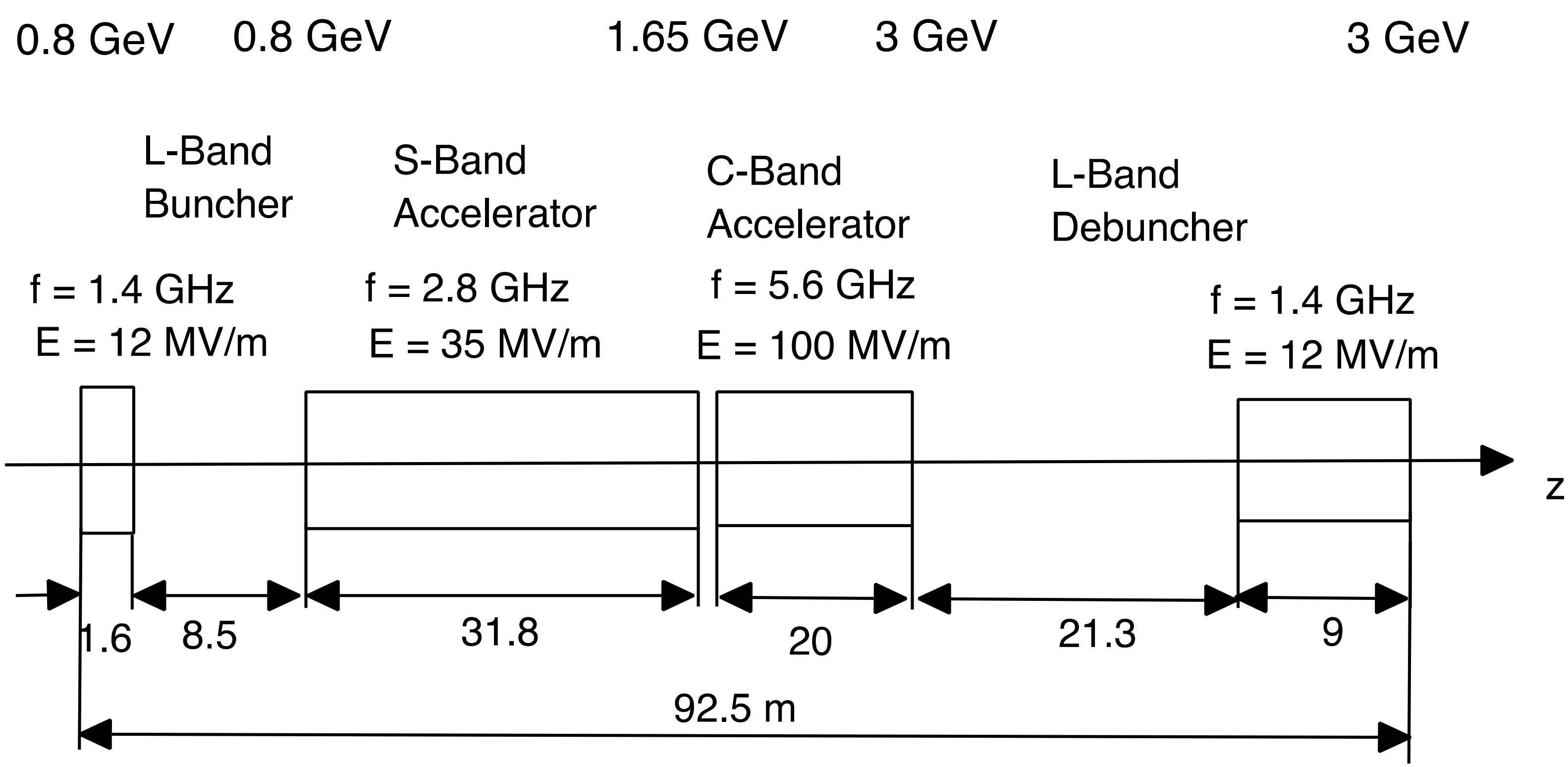
Time structure of LANSCE pRad beam



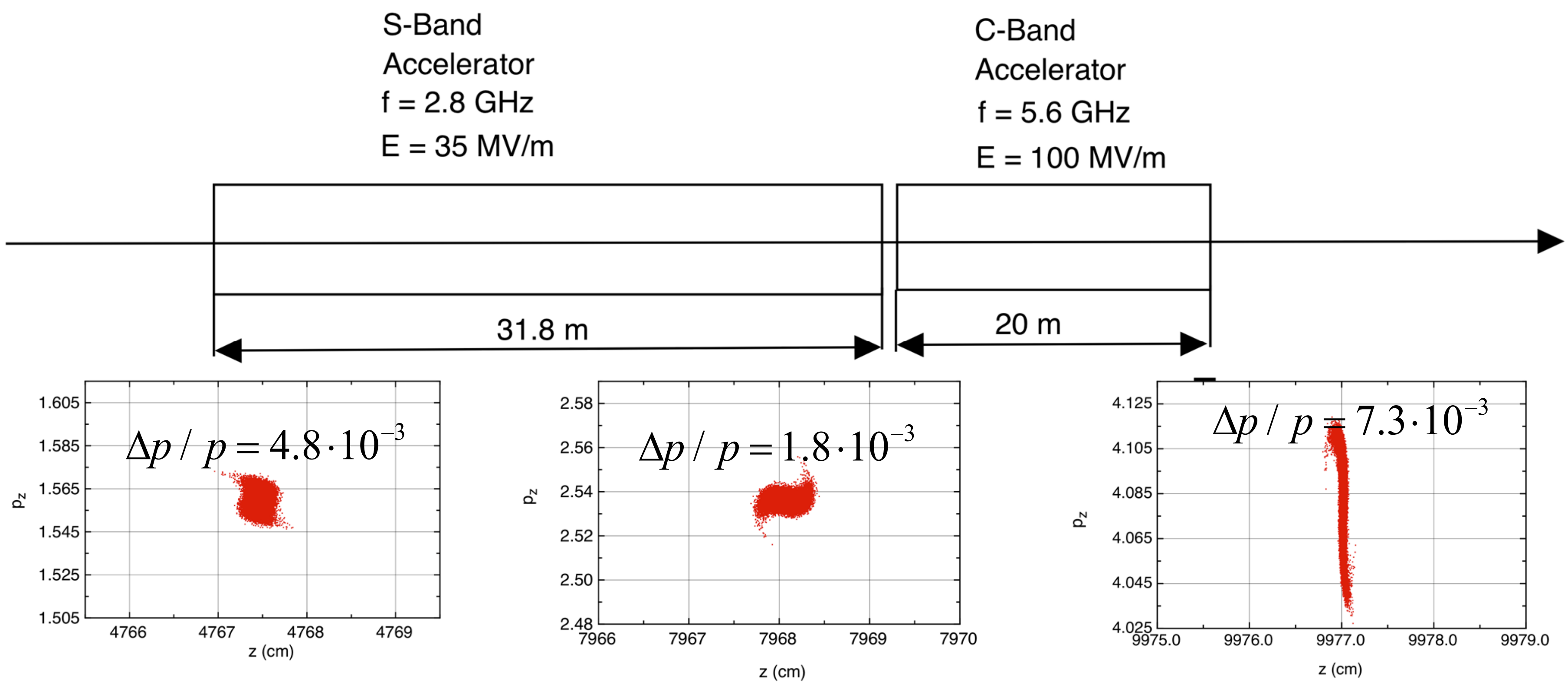
Design Issues for High-Gradient pRad Booster

1. Adaptation of high-gradient structures for protons
2. Prevention of beam loss and preservation of transverse acceptance
3. Mitigation of strong RF defocusing at high gradient
4. Selection of appropriate magnetic focusing
5. Matching of the 800-MeV LANSCE beam to high gradient structure
6. Beam de-bunching after linac to reduce momentum spread

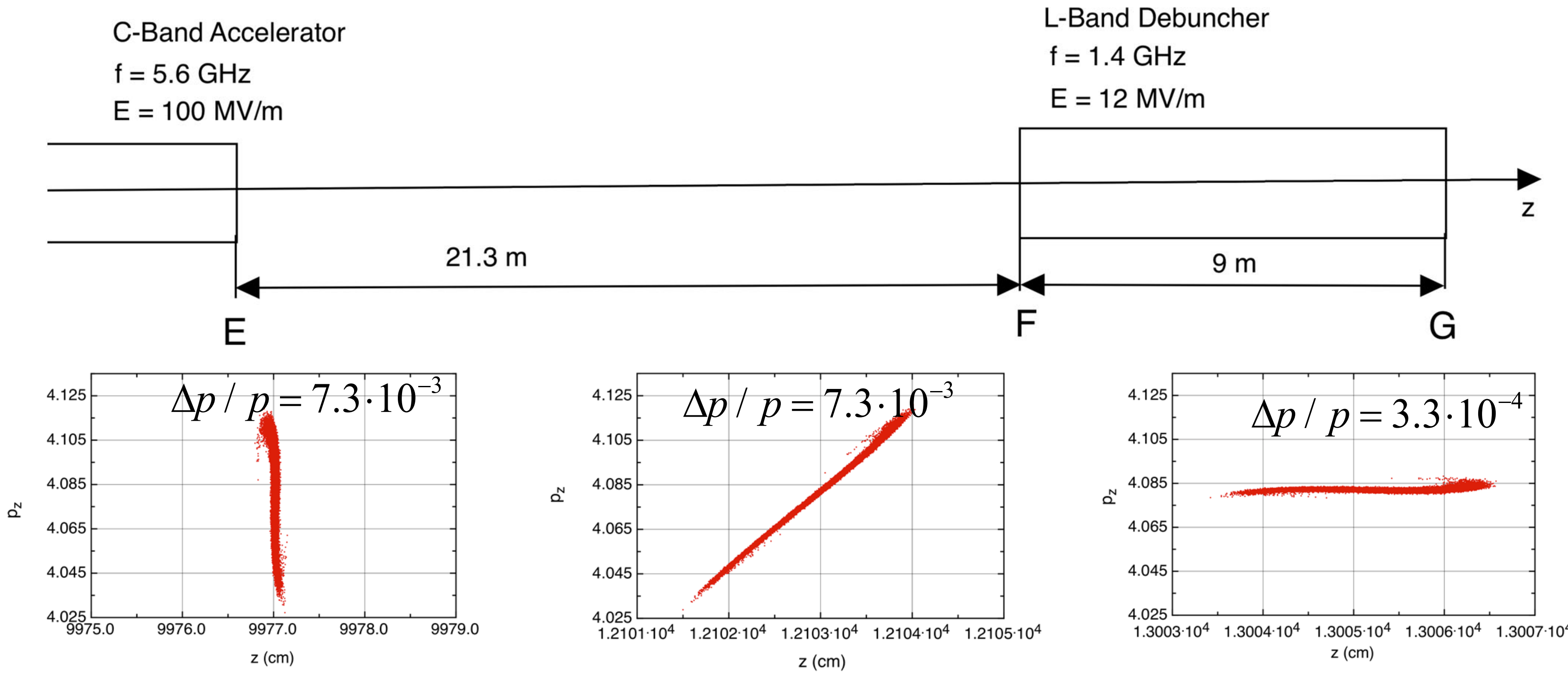
Proposed layout of the 3-GeV booster



Increased momentum spread due to C-band

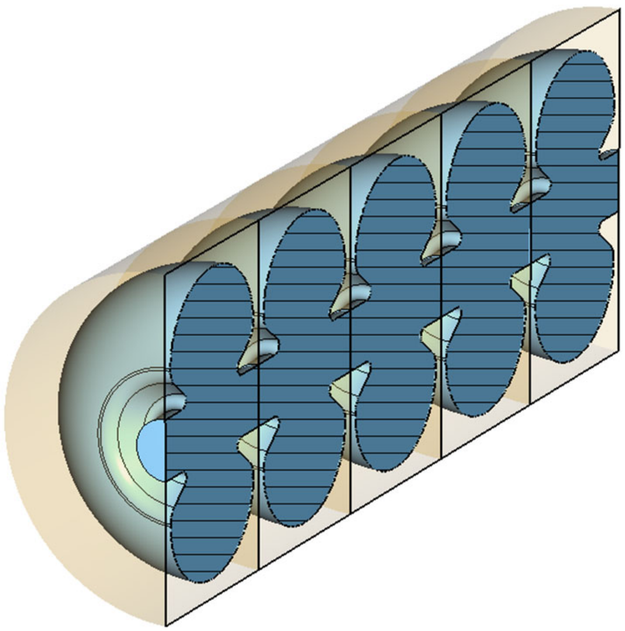


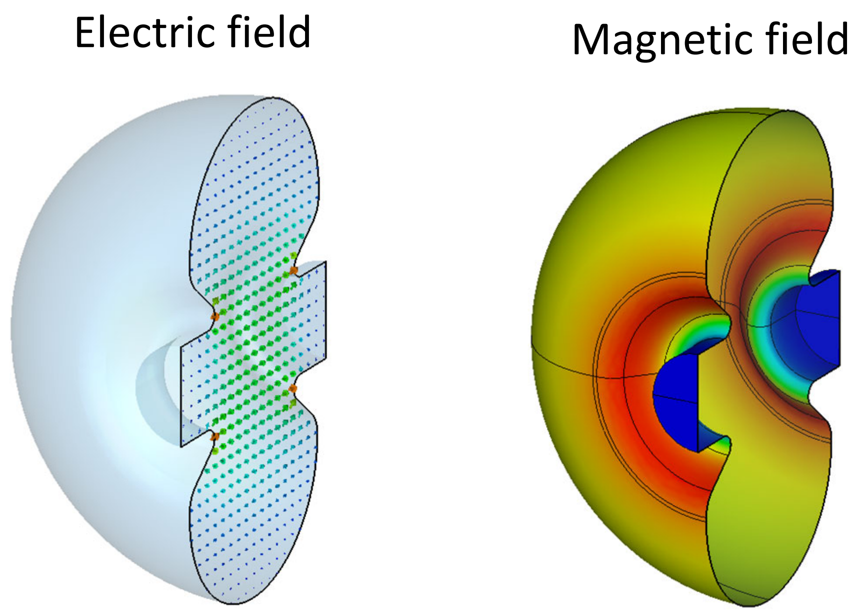
Momentum spread reduction



High gradient RF structures

The goal of RF structure design is to reduce peak surface fields to maximize the gradient.





RF breakdown theory

Figure of merit for material studies

- Tradeoffs:
  - **Good:** Adding solute atoms can improve strength: limit plastic deformation under thermal loading
  - **Bad:** Adding solute atoms can increase RF dissipation and thermal stresses: increase driving force for plastic deformation

- **Figure of merit** (FOM):
  - Critical stress to move dislocations / Thermal stress created by RF dissipation

- Chemical space: Dilute binary Cu alloys

LDRD 20200057DR

Calculating the Figure of merit

Calculating the Figure of merit requires:

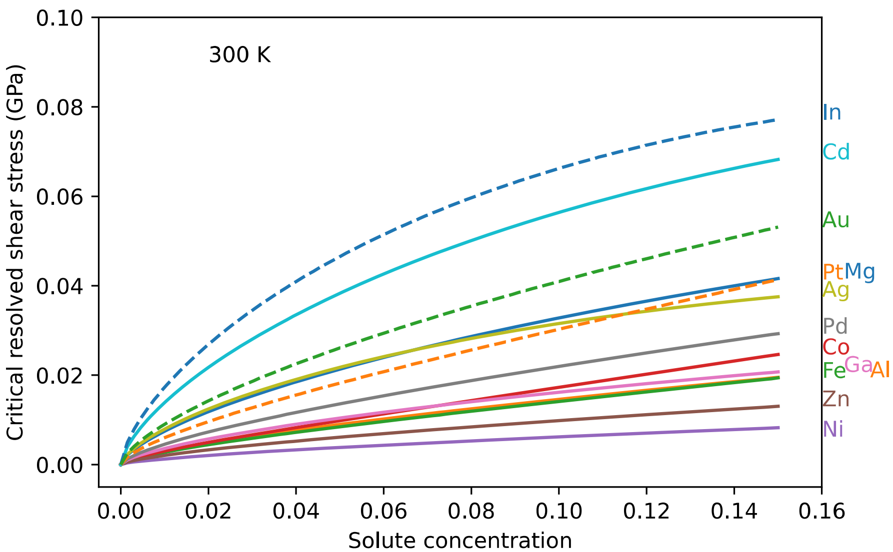
- Lattice constant: direct structure relaxation
- Mechanical properties: finite distortion
- Thermal expansion coefficient: quasi-harmonic approximation
- Electrical and thermal conductivity:
  - Boltzmann transport (Empirical relaxation time)
  - SPRKKR

These quantities need to be computed for different solute concentrations.

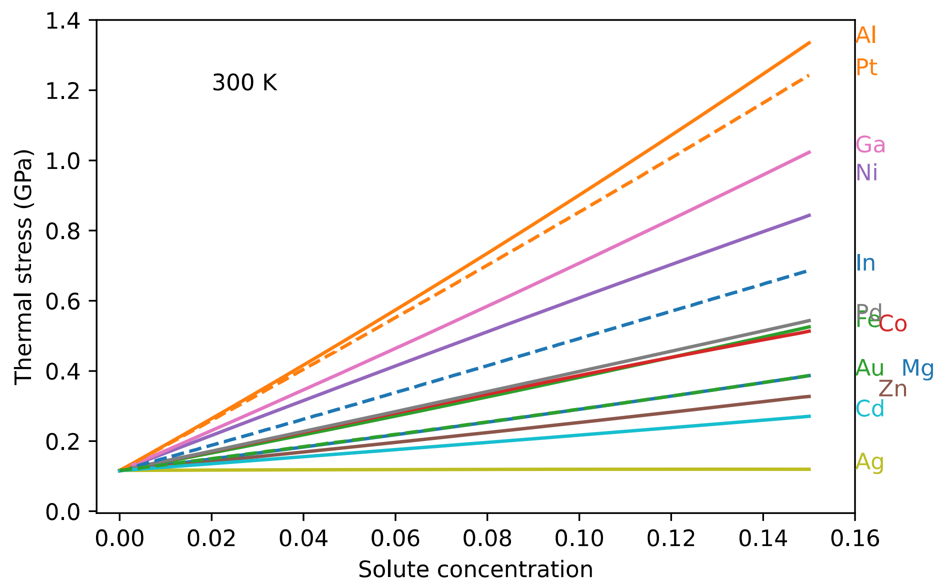
This requires tens of DFT calculations.

FOM computations results

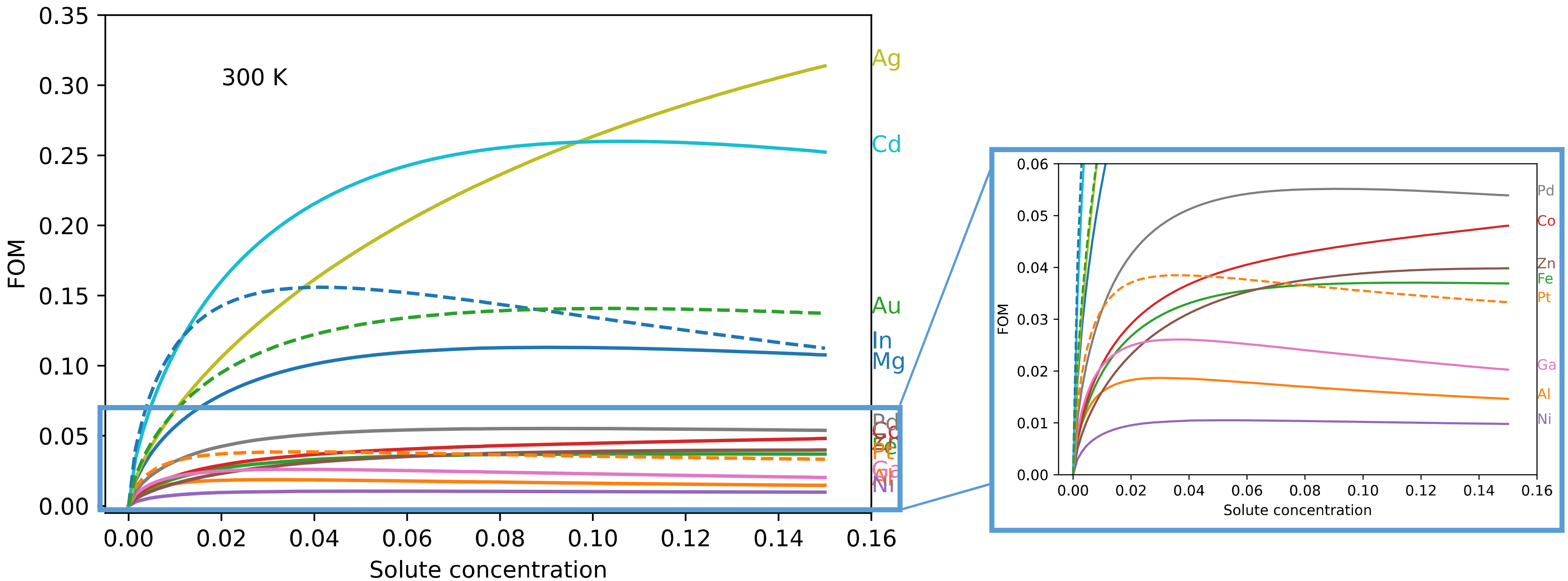
FOM #1: Critical stress to move dislocations



FOM #2: Thermal stress created by RF dissipation



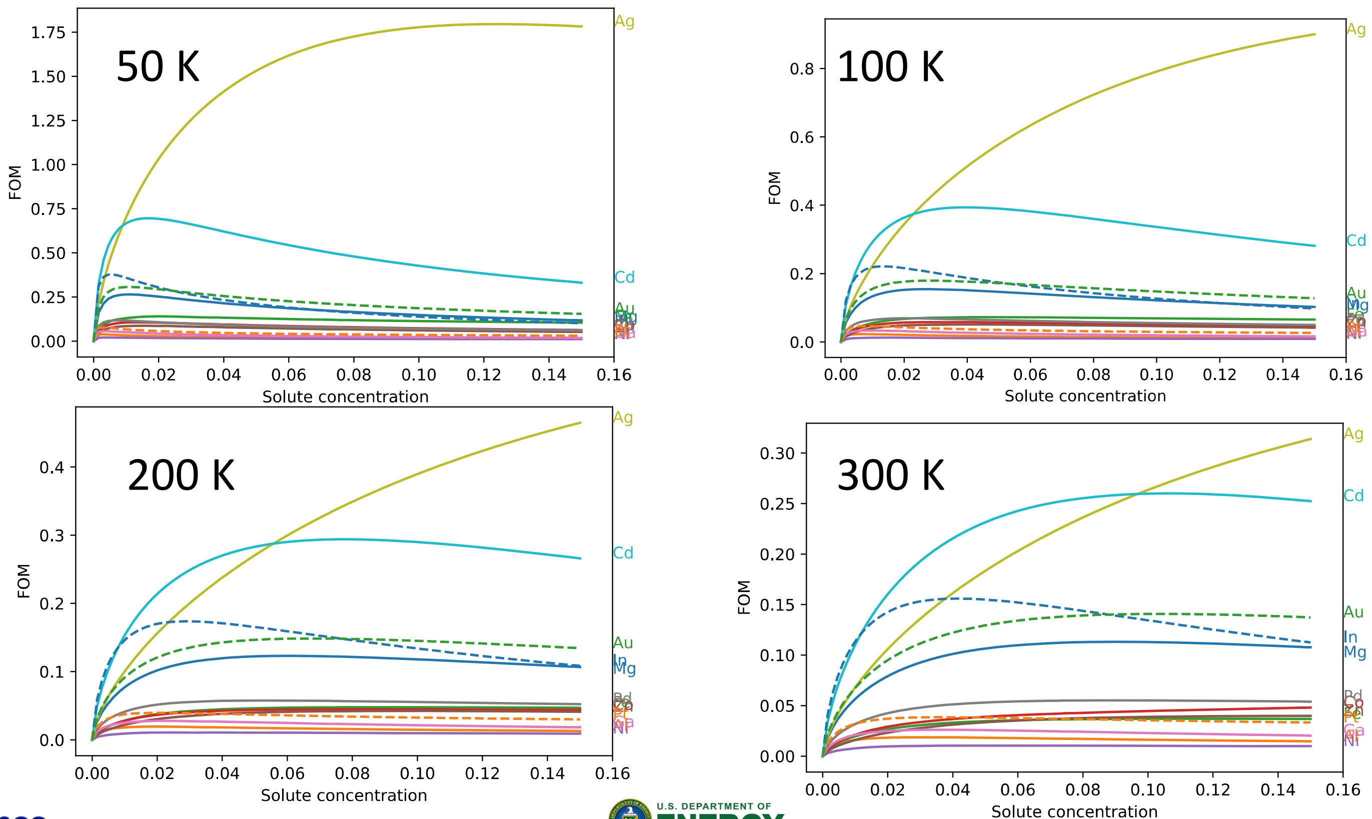
FOM #1/ FOM #2



Maximum solubility in copper:

Ag (5 at.% 1100K), Cd (2.07 at.% 820K), Mg (7 at.% 1008K), In (11 at.% 850K)

Temperature dependence of the FOM ratio



Summary and plans

LANL C-band Research Test Facility (CERF-NM)

- Continuous testing of RF cavities and components for high gradients.
- Establishing benchmark points for C-band.
- Providing high gradient test grounds for collaborators.
- Capability to be added: cryo-cooled cavity testing.

C-band accelerator for accelerator and material studies

- We aim to develop a C-band accelerator test facility for advanced cathode, accelerator, and material studies.
- A location was identified at TA53-0014, AFEL area.
- The bunker can accommodate 20 kW electron beam.
- Requires investments in infrastructure.
- Will become the first operational cryo-cooled copper accelerator in the world.
- Will provide 43 keV photon bursts for material studies

pRad upgrade

- High gradient C-band provides a cost-effective solution for pRad upgrade to 3 GeV.
- A complete design for the pRad upgrade based on C-band will be delivered by the on-going LDRD project.
- High gradient C-band accelerating structures for pRad upgrade will be tested at CERF-NM.

Further studies of materials in extremes

- LANL material studies are already recognized by the International High Gradient Collaboration: first theoretical explanation for the superior performance of copper-silver alloys.
- Theoretical studies of materials under extreme high field conditions add new capabilities to LANL microstructure-aware, multi-physics modelling frameworks.
- Supports LANL core material programs such as Advanced Engineering Materials (AEM) for thermal protection systems (TPS) applications.